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Research on computing position and orientation deviations caused by mating two non-ideal planes

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Abstract

This paper intends to research on computing the position and orientation deviations of the assembled part in an assembly when there are deviations from the mating non-ideal planes. Two types of Cartesian coordinate systems, global coordinate system and local coordinate system, are built. The position and orientation offsets between two coordinates are introduced to formulate the position and orientation deviations of the assembly. A progressive contact method is addressed: search for the deterministic contact state between the two mating non-ideal planes and then obtain the position and orientation offsets. An example of two square flange parts assembly is provided to validate the method.

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Keywords: Surface deviation; assembly deviation; position and orientation offset; contact state

1. Introduction

Surface deviation is inevitable on manufactured parts and it may influence the quality of assemblies. In this context, assembly problems with regard to surface deviations have been studied by numerous scholars and researchers. Zhang et al. [1,2] have studied the variation propagation control in mechanical assembly for direct-build, best-build and worst-build. The assembly of two-dimensional cylindrical parts was taken as an example in their work. Franciosa et al. [3] have proposed a numerical procedure to solve fully and over-constrained rigid assemblies with respect to variational features. Li et al. [4] have put forward a relative positioning scheme to determine the positions of variant polyhedral parts in 3D assemblies. Gao et al. [5] have presented the DLM method for tolerance analysis of three-dimensional mechanical assemblies in which assembly variation models can be generalized to include small kinematic adjustments between mating parts.

Efforts on surface deviation representations have been put forward as well. Qiao et al. [6] have presented a surface deviation representation method in which a deviation coordinate system is constructed on the nominal surface by adding a deviation dimension on curvilinear coordinate system. The method can facilitate the explicit and convenient representation of non-ideal surfaces, and make it more convenient for assembly simulation. Schleich et al. [7,8] have established skin model shapes with systematic deviations and random deviations, and their approach for the assembly simulation of skin model shapes has simultaneously been studied. Samper et al. [9] have studied the assembly process through a method in which non-ideal surfaces are described by a geometrical model based on the modal shapes of the ideal surface. The method can compute the completely deterministic contact points between two mating surfaces.

Moreover, the relative positioning between two assembly parts with surface deviations has been studied as well. Stockinger et al. [10] have presented a relative positioning method to perform a geometrically correct simulation of part assembly in which the realistic deviations of assembly parts can be generated by means of Finite Element Analysis (FEA). In order to determine the relative positioning influenced by the contact, an approach for the contact simulation of Skin Model Shapes employing constrained registration methods has been proposed in [11]. Li et al. [12] has proposed a method by which

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assembly clearance between two mating surfaces with regard to deviations can be expressed graphically. The method is capable of checking the relative positioning status between two assembly parts.

This paper intends to research on computing the assembly deviations in position and orientation caused by mating two non-ideal planes, and provides a new idea for further research on assembly problems with respect to surface deviations.

2. Representation of the position and orientation deviation

2.1. Analysis of position and orientation deviation

The position and orientation deviation is the difference between the relative position and orientation in actual situation with regard to the surface deviation and the relative position and orientation in ideal situation. The two relative position and orientation reflects the relation of two coordinate systems which are separately built on ideal surfaces corresponding to the two mating surfaces. The coordinate systems on the two ideal surfaces coincide with each other in ideal situation. In contrast, in actual situation, there exist position and orientation offsets between them because of the surface deviation. Consequently, position and orientation deviation comes into existence.

Depending upon the six-point locating principle, three degrees of freedom between two mating non-ideal planes can be constrained with three non-collinear contact points. In other words, the deterministic contact state can be regarded as the state between two mating non-ideal planes with three non-collinear contact points. Hence, three position and orientation offsets between two coordinate systems on two ideal planes corresponding to the two mating non-ideal planes come into existence in the directions of the three constrained degrees of freedom. As a result, when two assembly parts are assembled together by a couple of mating non-ideal planes, the position and orientation deviations of two assembly parts can be represented by means of defining coordinate system, as well as computing three position and orientation offsets between two coordinate systems on ideal planes.

2.2. Definition of coordinate systems and deviations finding process

Two types of Cartesian coordinate systems, global coordinate system (GCS) and local coordinate system (LCS), are established as the basis of the calculation method. The GCS is regarded as the reference coordinate system, while the LCS is set on a certain point of the ideal plane. The non-ideal plane will be described in the local coordinate system. The initial coordinate direction of LCS is the same as GCS.

In this study, non-ideal plane *Pa* and non-ideal plane *Pb* are assumed to be mated with each other. Fig. 1 shows that GCS (denoted as *G*) is built and is marked as $O_GX_GY_GZ_G$, the LCS of *Pa* (denoted as *La*) is built and is marked as $O_{La}X_{La}Y_{La}Z_{La}$, while the LCS of *Pb* (denoted as *Lb*) is built and is marked as $O_{Lb}X_{Lb}Y_{Lb}Z_{Lb}$.

With the defined coordinate systems, the relationship of the two non-ideal planes as well as the corresponding process finding the deviations when the two mating planes are in contact can be described in the following.

Set the two LCSs coincide with each other. There is no position and orientation deviation for the two planes. Under this circumstance, the two planes might be apart from each other or inserted into each other as they are non-ideal planes with real morphologies considered. In order to find a deterministic contact state, the distances of the corresponding points between the two planes should be computed and the one with the minimum actual value among them could be found. Subsequently, plane *Pa* should be moved relative to plane *Pb* along Z_G-axis. By the computed distance, the two planes contact only at the obtained point. The distance is the position deviation of the mating planes in that direction.

The two planes can rotate when there is only one contact point. Therefore, it is necessary to find a second contact point to limit the rotation. When the second point is obtained, the angle of plane *Pa* rotating relative to *Pb* around the first contact point to reach the second contact point is regard as one of the orientation deviations. When the two planes contact by two contact points, they can still rotate toward one direction. Thus a third contact point must be found to limit the rotation. When the third contact point is obtained, because of the first two contact points, the plane *Pa* will rotate an angle around the connection of the two points, and the angle is another orientation deviation for the two mating non-ideal planes.

2.3. Representation of position and orientation deviation by position and orientation offsets

The position and orientation deviations of two assembly parts should be described by six position and orientation offsets in the directions of six degrees of freedom. Based on the analysis of position and orientation deviation, when two parts are assembled by two mating non-ideal planes, only three position and orientation offsets in the directions of the three constrained degrees of freedom are required to represent the position and orientation deviations. One of the three position and orientation offsets is translational while the others are rotational position and orientation offsets.

According to the direction of *La*, as well as *Lb* as shown in Fig.1, the translational position and orientation offset is denoted as t_z which corresponds to the restricted degree of translational freedom in the direction of Z_G-axis. One of the two rotational position and orientation offsets is denoted as δ_x which corresponds to the constrained degrees of rotational freedom in the direction of X_G-axis. And the other one is simultaneously denoted as δ_y which corresponds to the restricted degrees of rotational freedom in the direction of Y_G-axis.

Consequently, the position and orientation deviations of two parts assembled together by *Pa* and *Pb* (denoted as POD_{ab}) can be represented as:

$$POD_{ab} = (t_z,\ \delta_x,\ \delta_y) \tag{1}$$

The method for computing t_z, δ_x and δ_y will be introduced in the next section.

3. Progressive contact method

3.1. Principle of progressive contact method

Based on the analysis of the mating process between two non-ideal planes, the process of generating t_z, δ_x and δ_y can be considered as the process of relocating relative position and orientation between LCSs from ideal situation to actual situation with respect to surface deviation.

During the mating process, when each contact point is determined successively, the position and orientation offsets will be obtained accordingly. At the end of the process, the deterministic contact state is achieved due to the ascertainment of the three non-collinear contact points. Consequently, the three position and orientation offsets are acquired.

The method in which the mating non-ideal planes contact progressively, can be put forward for achieving the deterministic contact state, as well as the three non-collinear contact points in sequence. So that the three position and orientation offsets can be computed. The method is named as progressive contact method in this paper.

3.2. The computing process of progressive contact method

The computing process can be divided into 4 stages, as shown in Fig. 1.

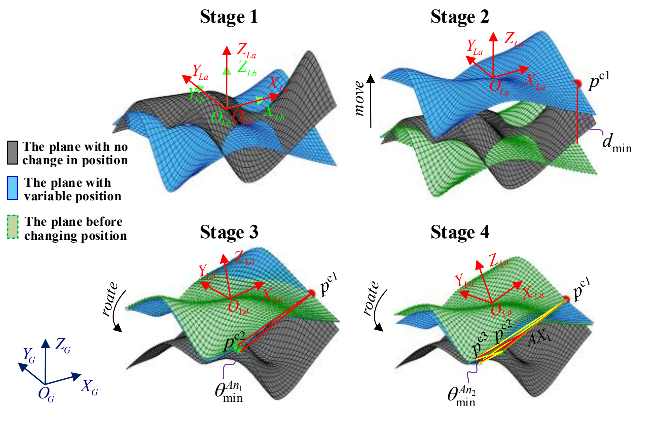

Fig. 1. The process of progressive contact method

Stage 1 is about preprocessing of the given planes. The mating non-ideal planes should be provided by point clouds. The number of the point clouds n should be appropriately selected, because the more n is, the more reasonable the computing result will be. Whereas, the computing efficiency will become lower simultaneously. After the coordinate systems are built, La and Lb should be coincided with each other, as shown in Stage 1 in Fig. 1.

Translational position and orientation offset t_z will be obtained in Stage 2. La moves along the Z_G-axis by a minimum distance to generate a contact state of the two planes: only one point is in contact. The distance might be either a positive value if the two mating planes are apart from each other without contact, or a negative value if the two planes have intersections when they mate as shown in Fig. 1. In calculating Stage 2 in Fig. 1, the first contact point p^{c1} can be found once the minimum actual value of the distance, which is the maximum absolute moving distance obtained when the two planes have negative distances, is found. This moving distance is t_z.

Let p^{Pa} and p^{Pb} be the corresponding points between Pa and Pb, and d as the distance between the two points in Z_G direction. d can be expressed as:

$$d = p_Z^{Pa} - p_Z^{Pb} \tag{2}$$

Compute the differences of the n pairs of corresponding points between Pa and Pb in Z_G direction, and the difference set D will be obtained. Finding the minimum element $d_{\min}$ in set D. Thus, t_z is computed as:

$$t_z = -d_{\min} \tag{3}$$

Rotational position and orientation offset δ_x will be calculated in Stage 3. La takes p^{c1} as the rotation point, and rotates in any direction. Different contact points can be acquired if rotating angles are different. The second contact point p^{c2} can be constructed once the minimum rotating angle $\theta_{\min}^{An_1}$ is obtained as shown in Stage 3 in Fig. 1. $\theta_{\min}^{An_1}$ can be computed by the minimum ratio of the distance of the two planes in corresponding point to the distance between point p^{c1} and the current point. This rotated angle value is δ_x.

The computing process is described as follows.

Build vector with p^{c1} and other points on Pa, as well as on Pb. v^{1Pa} and v^{1Pb} should be computed as:

$$v^{1Pa} = (p_X^{Pa} - p_X^{c1}, p_Y^{Pa} - p_Y^{c1}, p_Z^{Pa} - p_Z^{c1}) \tag{4}$$

$$v^{1Pb} = (p_X^{Pb} - p_X^{c1}, p_Y^{Pb} - p_Y^{c1}, p_Z^{Pb} - p_Z^{c1}) \tag{5}$$

There are n-1 vectors which can be built on Pa, as well as on Pb, so that the vector set V^{1Pa} and vector set V^{1Pb} will be obtained. Angle θ^{An_1} of the corresponding vectors between set V^{1Pa} and set V^{1Pb} should be computed as:

$$\theta^{An_1} = \arccos(v^{1Pa} \cdot v^{1Pb} / \left|v^{1Pa}\right| \times \left|v^{1Pb}\right|) \tag{6}$$

Compute all the n-1 angles of the corresponding vectors between set V^{1Pa} and set V^{1Pb}. Thus, angle set An_1 will be acquired. The minimum element $\theta_{\min}^{An_1}$ should be found in set An_1.

Furthermore, the magnitude of the position and orientation offset can be regard as a small amount relative to the mating surface geometry size, which satisfies the differential assumptions. Therefore, δ_x is computed as:

$$\delta_x = \sin(-\theta_{\min}^{An_1}) \tag{7}$$

Rotational position and orientation offset δ_y will be obtained in Stage 4. Rotate Pa around line AX_1 of point p^{c1} and p^{c2} to find different contact points of the two planes. Calculate the rotating angle θ^{An_2} by the ratio of the distance of the two planes in corresponding point to the distance between the point to line AX_1 and find the third contact point p^{c3} when the minimum rotating angle $\theta_{\min}^{An_2}$ is obtained, see in Stage 4 in Fig. 1. The value of the angle is δ_y.

Relevant expressions are in the following.

Build vector with p^{c2} and other points on Pa, as well as on Pb. v^{2Pa} and v^{2Pb} should be computed as:

$$v^{2Pa} = (p_X^{Pa} - p_X^{c2}, p_Y^{Pa} - p_Y^{c2}, p_Z^{Pa} - p_Z^{c2}) \tag{8}$$

$$v^{2Pb} = (p_X^{Pb} - p_X^{c2}, p_Y^{Pb} - p_Y^{c2}, p_Z^{Pb} - p_Z^{c2}) \tag{9}$$

There are n-1 vectors which can be built on Pa, as well as on Pb, so that vector set V^{2Pa} and vector set V^{2Pb} will be obtained. Normal vector should be computed by the corresponding vectors between set V^{1Pa} and set V^{2Pa}, as well as set V^{1Pb} and set V^{2Pb}. v^{NPa} and v^{NPb} should be computed as:

$$v^{NPa} = v^{1Pa} \times v^{2Pa} \tag{10}$$

$$v^{NPb} = v^{1Pb} \times v^{2Pb} \tag{11}$$

Build all the n-1 normal vectors by the corresponding vectors between set V^{1Pa} and set V^{2Pa}, so that normal vector set V^{NPa} and set V^{NPb} will be obtained. Angle θ^{An_2} of corresponding vectors between set V^{NPa} and set V^{NPb} should be computed as:

$$\theta^{An_2} = \arccos(v^{NPa} \cdot v^{NPb} / \left|v^{NPa}\right| \times \left|v^{NPb}\right|) \tag{12}$$

Compute all the n-1 angles of the corresponding vectors between set V^{NPa} and set V^{NPb}, thus, angle set An_2 will be obtained. The minimum element $\theta_{\min}^{An_2}$ should be found in An_2.

As the position and orientation offset satisfies the differential assumptions, δ_y is computed as:

$$\delta_y = \sin(-\theta_{\min}^{An_2}) \tag{13}$$

The procedure of the progressive contact method for the three position and orientation offsets is depicted in Fig. 2.

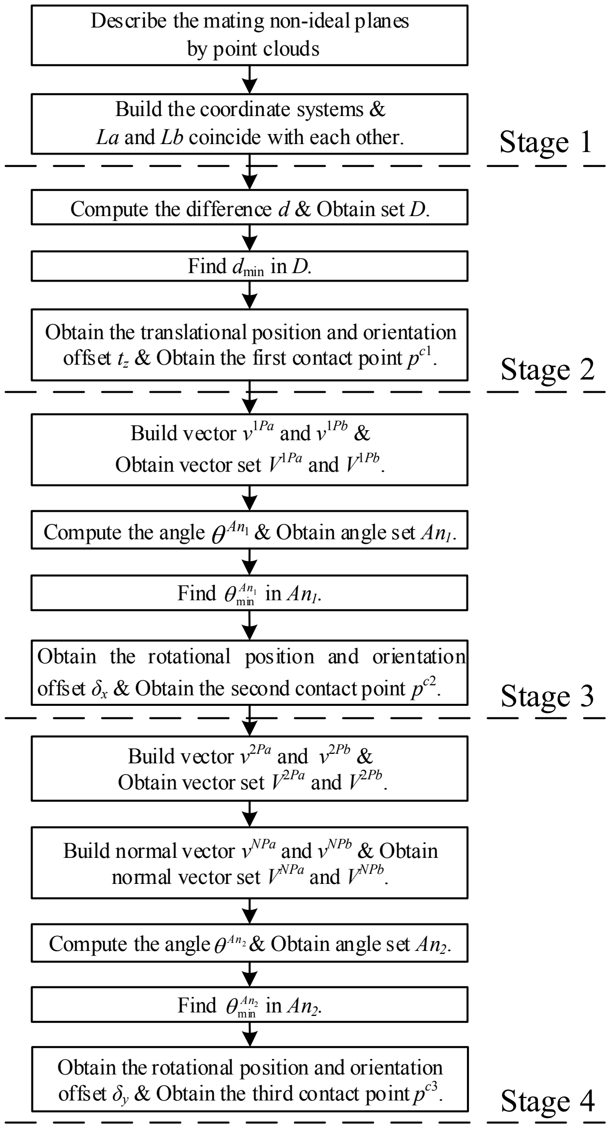

Fig. 2. The procedure of the progressive contact method

4. Case study

Considering the application of flange connection in assembly structures, an assembly example of two square flange parts is presented to validate the method. The two square flange parts are assembled together by two mating planes, as shown in Fig. 3. The side of the square mating planes is 300 mm in length, as shown in Fig. 4.

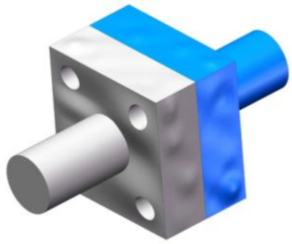

Fig. 3. The assembly of square flange parts

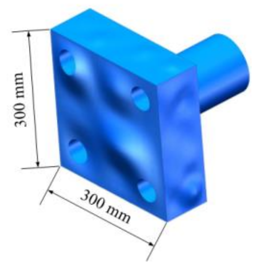

Fig. 4. The square flange part

Both the mating planes in this case are provided by 10201 points which are in 101 order square point clouds. The mating plane of the blue flange part is denoted as *Pb*, and the mating plane of the grey flange part is denoted as *Pg*.

The GCS (denoted as *G*) and two LCSs (denoted as *Lb* and *Lg*) are built, as shown in Stage 1 in Fig. 5. The origin of *Lb* and *Lg* can set at any point in *G*, and it is set at point (2.5, 2.5, 0) in this case.

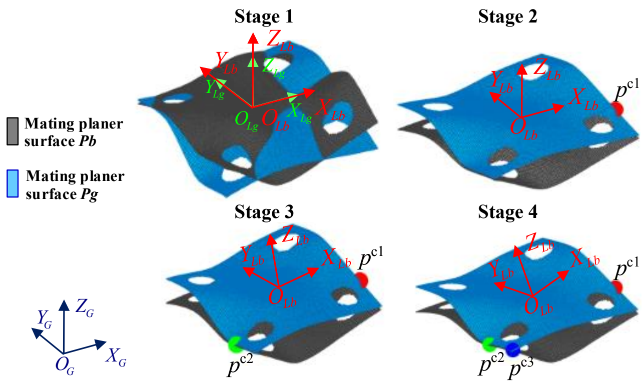

Fig. 5. The process for obtaining the deterministic contact state between *Pb* and *Pg* by progressive contact method

According to the progressive contact method in this paper, the three non-collinear contact points are determined separately through Stage 2, Stage 3 and Stage 4, as shown in Fig. 5. As a result, the three position and orientation offsets are obtained as, t_z=−1.48, δ_x=−0.026 and δ_y=−0.1, respectively. Therefore, the position and orientation deviations of the two square flange parts (denoted as POD_{bg}) are acquired by replacing t_z, δ_x and δ_y with the formula (1), that is:

$$POD_{bg} = (-1.48,\ -0.026,\ -0.1)$$

5. Conclusion

In this paper, the position and orientation deviations of two parts assembled together by two mating non-ideal planes have been formulated by one translational position and orientation offset and two rotational position and orientation offsets.

The proposed progressive contact method has been successfully validated for computing the three position and orientation offsets by finding the three non-collinear contact points separately. And it lays the foundation for future researches on assembly problems with respect to the surface deviations of mating non-ideal planes.

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